Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-50-TR–2007/002 September 2007
Hydromechanics Department Report

A Compendium of Resistance, Sinkage and Trim, and Longitudinal Wave Cut Measurements Obtained on Model 5365

by
Toby Ratcliffe
Anne Fullerton
James Rice
Don Walker
Lauren Russell
Thomas Fu

20070927452

Approved for Public Release; distribution unlimited.

NSWCCD-50-TR–2007/002 A Compendium of Resistance, Sinkage and Trim, and Longitudinal Wave Cut Measurements Obtained on Model 5365

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* September 2007	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* 1-Jul-2006 - 1-Mar-2007
4. TITLE AND SUBTITLE A Compendium of Resistance, Sinkage and Trim, and Longitudinal Wave Cut Measurements Obtained on Model 5365		**5a. CONTRACT NUMBER** N001406WX20713 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 0602123N
6. AUTHOR(S) Toby Ratcliffe, Anne Fullerton, James Rice, Don Walker, Lauren Russell, Thomas Fu		**5d. PROJECT NUMBER** R6721 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** 06-1-5600-461;06-1-5600-462
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Naval Surface Warfare Center Carderock Division 9500 Macarthur Boulevard West Bethesda, MD 20817-5700		**8. PERFORMING ORGANIZATION REPORT NUMBER** NSWCCD-50-TR-2007/002
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Patrick Purtell Code 331 Office of Naval Research 800 North Quincy Street Arlington, VA 22217-5660		**10. SPONSOR/MONITOR'S ACRONYM(S)** ONR **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Model 5365 is a 1/8.25th scale representation of the R/V Athena. This report documents both a new set of resistance, sinkage and trim, and longitudinal wave cut experiments as well as historical calm water resistance and sinkage and trim data which have been obtained on this model over the past few decades. The new resistance data were obtained in October and November of 2006 on Carriage 2 at the Naval Surface Warfare Center, Carderock, Division. In these experiments drag force was measured using both 6-component Kistler gages and a "traditional" block gage at the tow post location, as well as a Kistler gage located at the grasshopper bracket model attachment point. An in-situ calibration was also performed in order to verify loads at the tow post and grasshopper bracket location when a known load was applied to the system. Video and still digital cameras were also used to qualitatively characterize the wave field during the runs.

15. SUBJECT TERMS
model-scale resistance, sinkage and trim, longitudinal wave cuts

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Toby Ratcliffe
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	33 +vi	**19b. TELEPHONE NUMBER** *(include area code)* 301-227-7016

Contents

Figures

List of Tables

Abstract

Model 5365 is a 1/8.25th scale representation of the R/V Athena. This report documents both a new set of resistance, sinkage and trim, and longitudinal wave cut experiments as well as historical calm water resistance and sinkage and trim data which have been obtained on this model over the past few decades. The new resistance data were obtained in October and November of 2006 on Carriage 2 at the Naval Surface Warfare Center, Carderock, Division. In these experiments drag force was measured using both 6-component Kistler gages and a "traditional" block gage at the tow post location, as well as a Kistler gage located at the grasshopper bracket model attachment point. An in-situ calibration was also performed in order to verify loads at the tow post and grasshopper bracket location when a known load was applied to the system. Video and still digital cameras were also used to qualitatively characterize the wave field during the runs.

Administrative Information

The work described in this report was performed by the Maneuvering and Control Division (Code 5600). The work was sponsored by the Office of Naval Research as part of the Ship Wavebreaking and Bubbly Wake Program. The ONR Program Manager is Dr. L. Patrick Purtell (Code 331). The Project Leader at NSWCCD is Dr. Thomas Fu (Code 5600).

Acknowledgements

The authors would like to thank the assistance of the people who helped make this experiment successful. David Bochinski of Code 5600 provided his expertise in Kistler gage calibration and in-situ calibrations. David Grant, also of Code 5600, assisted with the detailed mechanical drawings necessary for fabrication of the mounting plates for the Kistler gages. Ryan Hanyok of the Imaging Section (Code 3441) of the Corporate Information Services Division (Code 3400) provided all the photographic support for this project.

Introduction

Model 5365 has recently been used by the Office of Naval Research (ONR) as the chosen hull form geometry to evaluate predictive Computational Fluid Dynamics (CFD) codes. (1,2) Two features of this model design have contributed to increasing interest in this hull form for CFD validation: the large speed range of the model, corresponding to 6 - 35 knots full scale representing a Froude number range from 0.14 - 0.83, and the transom stern geometry of the hull form which is realistic of a naval combatant. The model was tested prior to this in October 2004. (3) At that time the resistance measurements were called in to question because they were lower than those obtained in previous experiments. One of the goals of the experiment documented in this report was to repeat those resistance experiments while trying to document any "missing" sources of resistance.

In conjunction with the model tests, three full-scale experiments were performed on the R/V

Athena. The objective of these experiments was to quantify the free surface wave field, including areas of breaking waves, around the vessel. The experimental data was obtained using a laser light sheet technique called Quantitative Visualization.(4,5,6)

Model Description

Model 5365 is a 1/8.25 scale model of the R/V Athena, shown in Figure 1. The R/V Athena is a converted PG-84 Asheville-class patrol gunboat which is operated out of Naval Surface Warfare Center - Panama City Division as a high speed research vessel. The model, built in 1979, was constructed out of wood. The model has been refurbished over its life time, and in 2002 it was measured using NSWC's laser tracker model measurement system. The detailed measurements of the model, shown in Figure 2, reveal an asymmetry in the hull in the region of the stem, on the starboard side of the model. This as-measured geometry is available from NSWCCD by request.

Figure 1 - R/V Athena

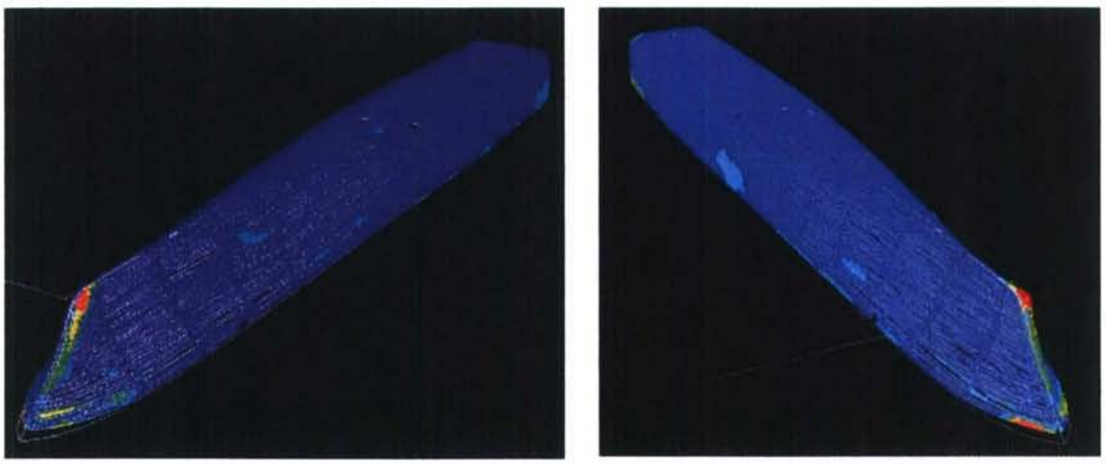


Figure 2 - Laser Tracker Surface Measurements of Model 5365 (largest deviation is 1.0 mm (0.04 inches) shown in red)

The model was painted yellow on the port side to facilitate still and video photography, and black on starboard side, providing a non-reflective surface for Q-Viz laser measurements. Turbulence studs were placed on the model along a line parallel to the stem and 2 inches aft of it. The turbulent studs are acrylic cylinders, 1/8" high, with a diameter of 1/8". Table 1 shows the model and full-scale hull form characteristics. The model was tested at a displacement condition corresponding to the displacement of the full scale Athena as tested during the 2004 ONR Athena Field Test. (5)

Table 1 - Model 5365 and Full-Scale (R/V Athena) Hull Form Characteristics

	Model Scale	**Full Scale**
Displacement	397 kg (875 lbs)	229 metric tons (225 long tons)
Draft (hull)	0.19 m (0.618 ft)	1.6 m (5.1 ft)
Maximum Beam	0.84 m (2.74 ft)	6.9 m (22.6 ft)
Transom Beam	0.70 m (2.3 ft)	5.8 m (19.0 ft)
LBP	5.69 m (18.67 ft)	46.9 m (154.0 ft)
Scale Ratio	8.25	

Model Resistance Measurements

In order to obtain model resistance measurements, and to answer questions raised about possible "stiction" when the model was tested in 2004, the model was outfitted with both "traditional" block gages and six-component force and moment "Kistler" gages. Photographs of the block gage and Kistler gages intstalled at the model tow post and at the grasshopper, are shown in Figures 3 and 4.

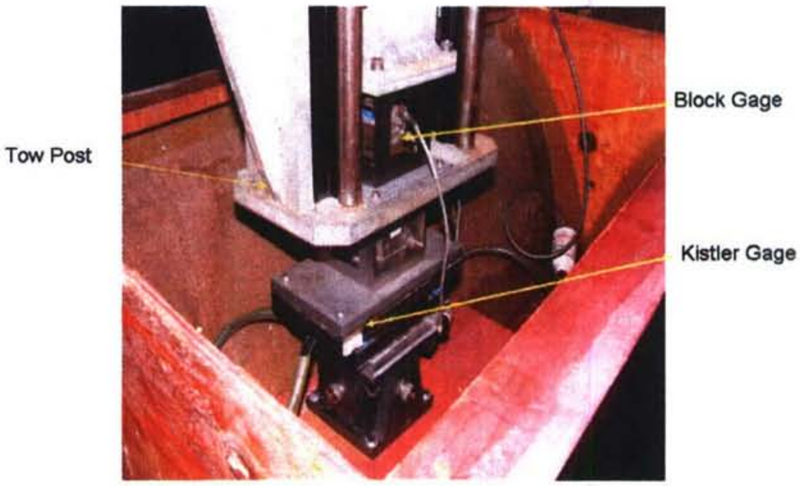


Figure 3 – Kistler Gage and Block Gage Installed at the Forward Tow Post Location

Figure 4 - Kistler gages mounted at the grasshopper location

Block Gage Calibration:

Block gage calibrations are done in the calibration lab located in Bldg. 4E at NSWCCD. A weight pan is attached to a pulley and connected to the block gage, as shown in Figure 5. A computer collects 5-second samples of data as 20-lb calibrated weights are added to the weight pan. The weights are added and then removed, with the process being repeated three times. A least-squared fit of the data is produced, resulting in a calibration factor which is used in the data collection and analysis program.

Figure 5 – Block Gage Calibration Stand

Kistler Gage Calibration: Calibration and Uncertainty Analysis for Kistler Gages 2002-3 and 2002-4

The "Kistler Gage" dynamometer was constructed using four Kistler force sensors capable of measuring force in 3 axes. The sensors were sandwiched between two plates of 1-inch thick heat-treated 17-4 stainless steel and preloaded as per manufacturer's specification. The voltages were recorded using a data record computer. The gage assembly is shown in Figure 6.

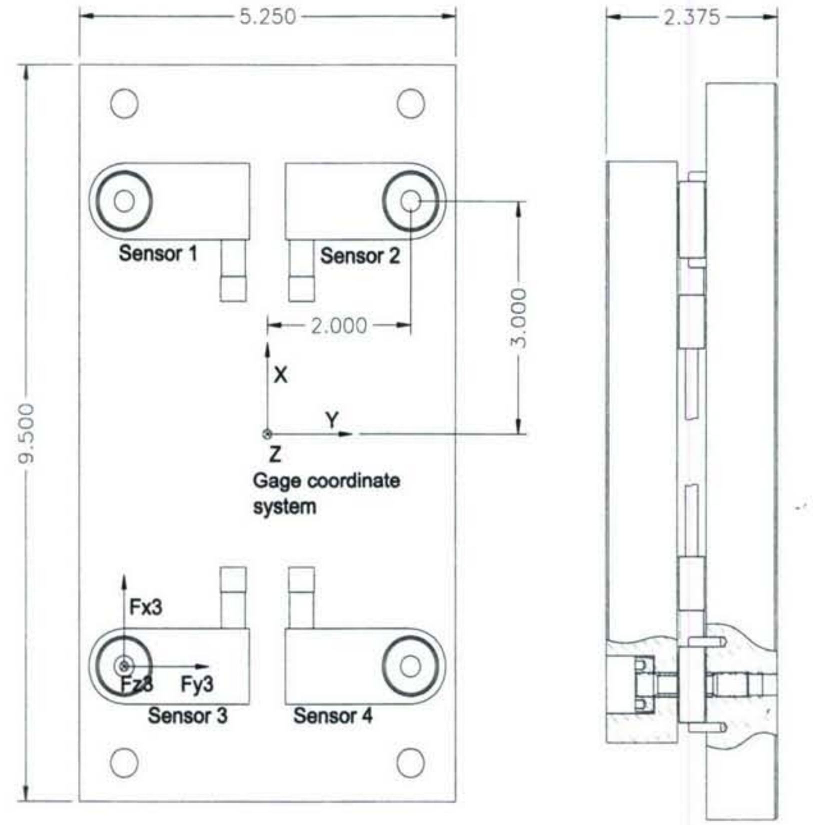


Figure 6 – Kistler Gage Dynamometer

To calibrate the dynamometer, calibrated dead weights were placed at specified load points. The input load and the output voltages were recorded for each load. Each axis was loaded in force and moment independently for a total of approximately 140 load points. The measurements were averaged for 2 seconds at 100 Hz sample rate. The voltages were converted to engineering units using the single axis calibrations performed prior to assembly of the gage. Since the sensor coordinate system did not always align with the gage coordinate system the forces from the sensors were rotated into the gage coordinate system. The forces and moments on the gage assembly were calculated using the following equations:

$$Fx_{sum} = Fx1 + Fx2 + Fx3 + Fx4$$

$Fy_{sum} = Fy1 + Fy2 + Fy3 + Fy4$
$Fz_{sum} = Fz1 + Fz2 + Fz3 + Fz4$

$Mx_{sum} = Ry * (-Fz1 + Fz2 - Fz3 + Fz4)$
$My_{sum} = Rx * (-Fz1 - Fz2 + Fz3 + Fz4)$
$Mz_{sum} = Ry * (Fx1 - Fx2 + Fx3 - Fx4) + Rx * (Fy1 + Fy2 - Fy3 - Fy4)$

The input loads and the calculated forces and moments above were used to generate an interaction matrix, A^{-1}, using Pseudo Inverse Technique as shown below.

$$\mathbf{F}_{sum} = \mathbf{F} * \mathbf{A}$$
$$\mathbf{A}^{-1} = ((\mathbf{F}^T * \mathbf{F})^{-1} * \mathbf{F}^T * \mathbf{F}_{sum})^{-1}$$

Where:

$\mathbf{F}_{sum}$ = a (6 x N) matrix containing forces and moments calculated from voltages
$\mathbf{F}$ = a (6 x N) matrix containing applied loads (forces and moments)

Then to derive an applied load given measured voltages:

$$\mathbf{F} = \mathbf{F}_{sum} * \mathbf{A}^{-1}$$

The error of the measurements was calculated:

$$\text{Error} = \mathbf{F} - \mathbf{F}_{sum}$$

Table 2 and Table 3 below summarize the calibration results of each gage. The max and min values represent the maximum and minimum errors over the whole range of the calibration. The largest error in forces for the 1st gage (2002-3) was 0.39% and in moments it was 1.12%. For the 2nd gage (2002-4) the largest error in forces was 1.42% and in moments it was 0.57%.

Table 2 - Calibration results for Kistler Dynamometer Serial 2002-3

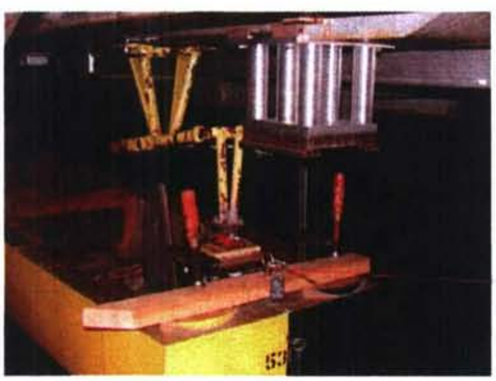
Serial	FX	FY	FZ	MX	MY	MZ
2002-3	(lbs)	(lbs)	(lbs)	(ft-lbs)	(ft-lbs)	(ft-lbs)
Range	400	400	765.4	100	200	150
%Error						
Max	0.24	0.13	0.03	0.15	0.27	0.21
Min	-0.27	-0.39	-0.20	-1.12	-0.27	-0.33
	FX	FY	FZ	MX	MY	MZ
ERROR	(lbs)	(lbs)	(lbs)	(ft-lbs)	(ft-lbs)	(ft-lbs)
MAX	0.97	0.53	0.23	0.15	0.55	0.32
MIN	-1.07	-1.56	-1.51	-1.12	-0.54	-0.49
STDEV	0.29	0.38	0.40	0.13	0.15	0.15

Table 3 - Calibration results for Kistler Dynamometer Serial 2002-4

Serial	FX	FY	FZ	MX	MY	MZ
2002-4	(lbs)	(lbs)	(lbs)	(ft-lbs)	(ft-lbs)	(ft-lbs)
Range	100	100	400	100	100	150
%Error						
Max	1.42	1.27	0.10	0.32	0.23	0.40
Min	-0.74	-0.57	-0.22	-0.24	-0.57	-0.27
	FX	FY	FZ	MX	MY	MZ
ERROR	(lbs)	(lbs)	(lbs)	(ft-lbs)	(ft-lbs)	(ft-lbs)
MAX	1.42	1.27	0.38	0.32	0.23	0.60
MIN	-0.74	-0.57	-0.87	-0.24	-0.57	-0.41
STDEV	0.33	0.37	0.25	0.07	0.15	0.17

In-Situ Calibration:

An in-situ calibration was performed for the single tow post with grasshopper towing arrangement. The model was pulled from a location in stern as shown in Figure 7. Successive, calibrated, twenty-pound weights were added to the pan balance, which was located in the dry-dock, until one hundred pounds was reached, and then the calibration weights were successively removed. Figure 8 presents the results from this in-situ calibration. The errors from the in-situ calibration were largest for the block gage and aft Kistler, accounting for as much as 4 % of the total load. The error for both gage sums (forward and aft Kistler, and block gage and aft Kistler) decreases as the load weight is increased. The errors emerging from the in-situ calibrations were not large enough to account for the unusually low resistance measured at the tow point during the 2004 experiments, but they did justify measuring drag forces at both the tow post and the grasshopper during this set of experiments.


Cable for applying "tow force"

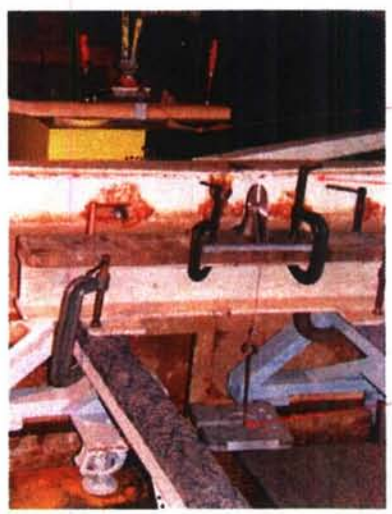

Cable for applying "tow force"
Dry-dock door
Weight pan to hold calibration weights

Figure 7 – In-Situ calibration Set-up

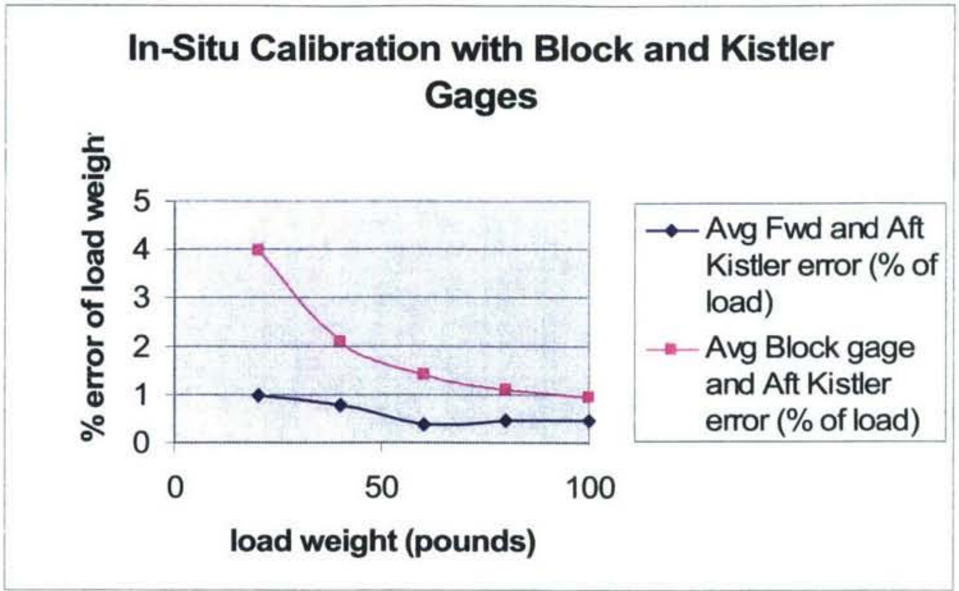


Figure 8 – In-Situ Calibration Results from Free-to-Sink and Trim model

Discussion of Model Resistance Results:

The current set of resistance data has been plotted with the historic data and is presented in Figure 9. The new data are consistent with the data obtained in 1979 (7) at a slightly higher model displacement. The resistance data is presented in tabular form in Tables 4 and 5. The data for both the block gage and the Kistler gages are shown here. The largest difference between the two different gage summations, over the entire speed range, was 1.4% at a speed corresponding to 9 knots full scale (in data set 2.)

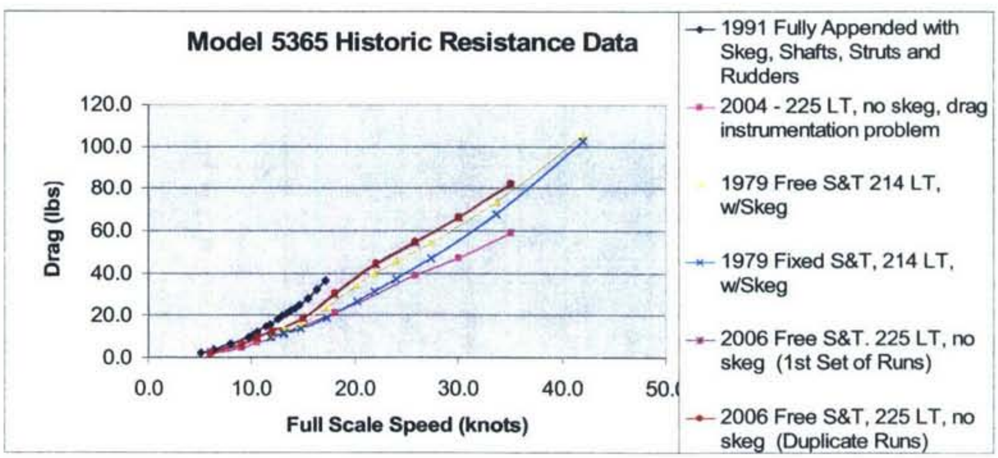


Figure 9 – Historic Resistance Data

Table 4 – Free-to-Sink-and-Trim Drag Data with Block Gage and Kistler Gage Instrumentation; Data Set 1

Speed		Fr	Block Gage Drag (lbs)	Fwd Kistler Drag (lbs)	Aft Kistler Drag (lbs)	FWD + AFT Kistler (lbs)	BGDrag +Aft Kistler (lbs)
Full-Scale (kts)	Model Scale (kts)						
6.0	2.09	0.14	2.94	2.94	-0.05	2.9	2.9
9.0	3.13	0.21	6.85	6.86	0.09	6.9	6.9
10.5	3.66	0.25	9.75	9.80	0.01	9.8	9.8
12.0	4.18	0.29	12.84	12.92	0.06	13	13
15.0	5.22	0.36	19.04	19.15	0.03	19	19
18.0	6.27	0.43	30.32	30.53	-0.11	30	30
22.0	7.66	0.53	44.69	45.02	-0.31	45	44
25.8	8.98	0.62	54.71	55.24	-0.38	55	54
30.0	10.44	0.72	66.32	67.09	-0.49	67	66
35.0	12.19	0.83	81.67	82.37	-0.38	82	81

Table 5 – Free-to-Sink-and-Trim Drag Data with Block Gage and Kistler Gage Instrumentation; Data Set 2

Speed		Fr	Block Gage Drag (lbs)	Fwd Kistler Drag (lbs)	Aft Kistler Drag (lbs)	FWD + AFT Kistler (lbs)	BGDrag +Aft Kistler (lbs)
Full-Scale (kts)	Model Scale (kts)						
6.0	2.09	0.14	2.86	2.88	-0.05	2.8	2.8
9.0	3.13	0.21	6.73	6.78	0.17	7.0	6.9
10.5	3.66	0.25	9.67	9.75	0.07	9.8	9.7
12.0	4.18	0.29	13.05	13.13	-0.06	13	13
15.0	5.22	0.36	19.04	19.18	0.14	19	19
18.0	6.27	0.43	30.72	30.87	-0.07	31	31
22.0	7.66	0.53	45.27	45.54	-0.31	45	45
25.8	8.98	0.62	55.40	55.91	-0.37	56	55
30.0	10.44	0.72	66.47	67.12	-0.40	67	66
35.0	12.19	0.83	82.36	83.08	-0.42	83	82

Model Sinkage and Trim Measurements

Model sinkage and trim measurements were made using two string potentiometerss attached to the model from the centerline tow beam. Eye screws were used to attach the strings to the model, near the forward and aft perpendiculars, repectively. The forward string potentiometer location was 1.75 inches (4.45 cm) forward of the forward perpendicular. The aft string potentiometer location was 221.85 inches (563.50 cm) aft of the forward string potentiometer location and 4.06 inches (10.3 cm) aft of the aft perpendicular.

The vertical displacements at the forward and aft perpendiculars are presented in Table 6. In order to compare data with the string potentiometers attached to the model at slightly different locations, and with different scale models tested at other facilities, the trim data has been plotted as a trim coefficient. This trim coefficient non-dimensionalizes the vertical displacements at the forward and aft perpendicular by the half-length of the model. The data obtained as part of this experiment are plotted along with historic trim coefficient data in Figure 10.

Table 6 – Model 5365 Average Trim Data

Froude Number	Full-Scale Speed (m/s (ft/s, knots))	Model-Scale Speed (m/s (ft/s, knots))	Forward Perpendicular Vertical Displacment (cm(in)) + bow up, - bow down	Aft Perpendicular Vertical Displacment (cm(in)) + stern up, - stern down
0.14	3.1 (10.1, 6.0)	1.08 (3.53, 2.09)	-0.150 (-0.059)	-0.094 (-0.037)
0.21	4.6 (15.2, 9.0)	1.62 (5.40, 3.14)	-0.401 (-0.158)	-0.386 (-0.152)
0.25	5.4 (17.7, 10.5)	1.88 (6.17, 3.66)	-0.488 (-0.192)	-0.599 (-0.236)
0.29	6.2 (20.3, 12.0)	2.15 (7.06, 4.18)	-0.551 (-0.217)	-0.923 (-0.366)
0.36	7.7 (25.3, 15)	2.69 (8.83, 5.23)	-0.662 (-0.261)	-1.615 (-0.636)
0.43	9.3 (30.4, 18)	3.22 (10.58,6.27)	0.980 (0.386)	-4.166 (-1.640)
0.53	11.3 (37.1, 22)	3.94 (12.95, 7.67	3.98 (1.566)	-6.292 (-2.477)
0.62	13.3 (43.5, 25.8)	4.62 (15.16, 8.99)	5.25 (2.068)	-6.311 (-2.485)
0.72	15.4 (50.6, 30.0)	5.37 (17.63, 10.45)	5.76 (2.270)	-5.766 (-2.270)
0.83	18.0 (59.1, 35)	6.27 (20.57, 12.19)	5.76 (2.270)	-5.298 (-2.086)

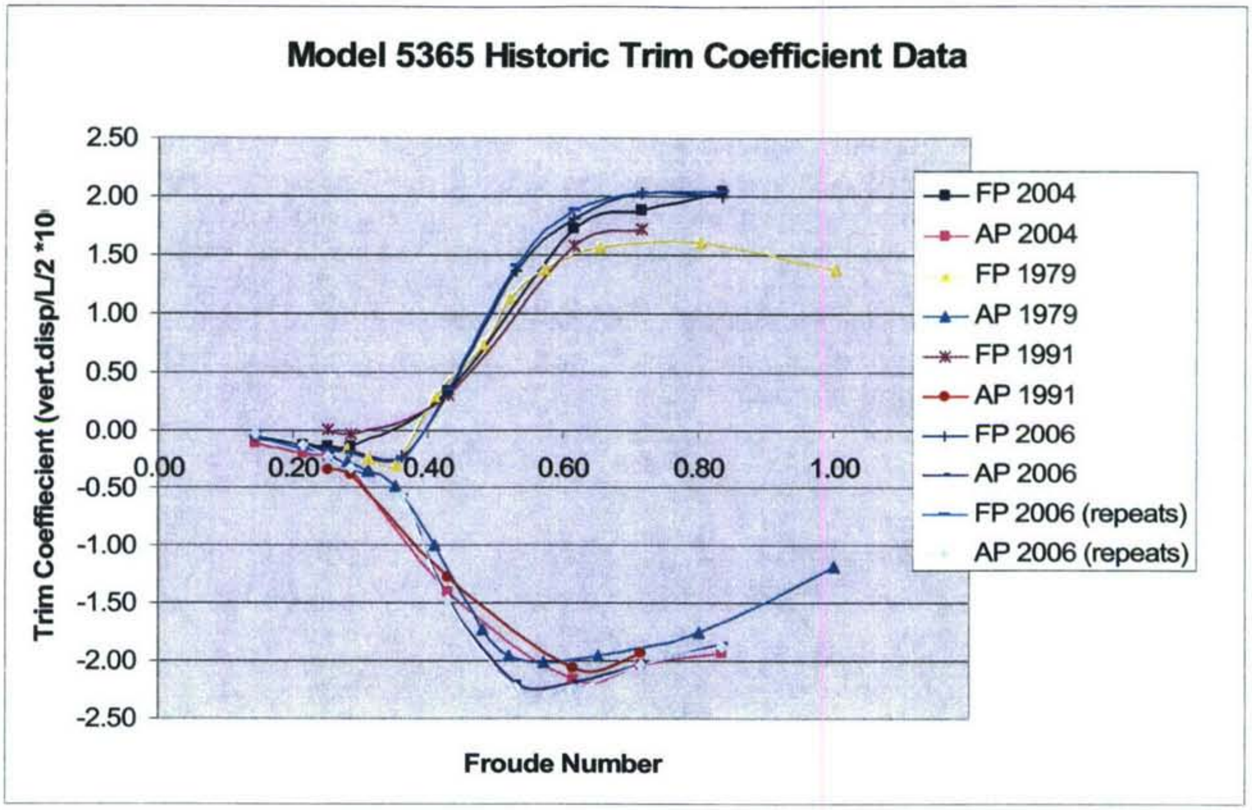


Figure 10 – Historic Trim Coefficicent Data

Longitudinal Wave Cuts

Longitudinal wave cuts were obtained using a modified and strengthened capacitance wave probe system, developed and constructed at NSWC. These wave cuts resulted in four off-body wave time-histories for each chosen speed. The data from the outer most probe was used to calculate wave pattern resistance.

Theory of Operation

The sensing element of the capacitance probe is a 30-gauge (AWG) solid silver-plated copper wire with 0.11 mm (0.045 in) kynar insulation, approximately 91 cm (36 in) in length. Attached to the sensing element is a weighted 1.2 m (4 ft) length of Mylar fishing line, used to provide probe stability in waves. The sensing element is suspended with half its length submerged in the basin. The basin water provides the ground reference for the sensing elements on the circuit card. With the copper wire completely insulated from the water, the sensing element behaves as a capacitor with one plate being the copper wire, the second plate the water, and the wire insulation acting as a dielectric. As waves in the basin change the submerged height of the sensing element, they change the effective capacitor plate size, which results in a change in capacitance. The change in capacitance is proportional to the wave height, which can then be calculated. By attaching the wave wire, a varying capacitor, to a timing circuit, a DC voltage is generated that is directly proportional to the capacitance of the probe and therefore, the wave height.

Experimental Setup

A truss section (wave boom), cantilevered from the basin wall over the water, provides a structure from which instrumentation is mounted, as shown in Figure 11. The wave boom extends 6.83 m (22.4 ft) from the basin wall, which is approximately 0.91 m (3 ft) short of the basin centerline. Mounted vertically on the wave boom is a motorized unislide traverse with an attached horizontal bar. The capacitance probes' electronics are mounted on the horizontal bar of the unislide. The unislide allows precise placement of the probes' vertical position, or probe emergence, used during static calibration of the probes. Four probes were used for this experiment. The position of the probes is referenced to the model centerline, with probe #1 being the closest inboard and probe #4 the farthest outboard. The probes' positions from the centerline of the model are given in Table 7.

Table 7 - Capacitance Probe Transverse Position

Probe #	Distance from Centerline (m (ft))	y/B_T
1	0.60 (1.98)	0.86
2	1.05 (3.45)	1.50
3	1.40 (4.60)	2.00
4	1.75 (5.75)	2.50

B_T = Maximum transom beam = 0.70 m (2.3 ft)

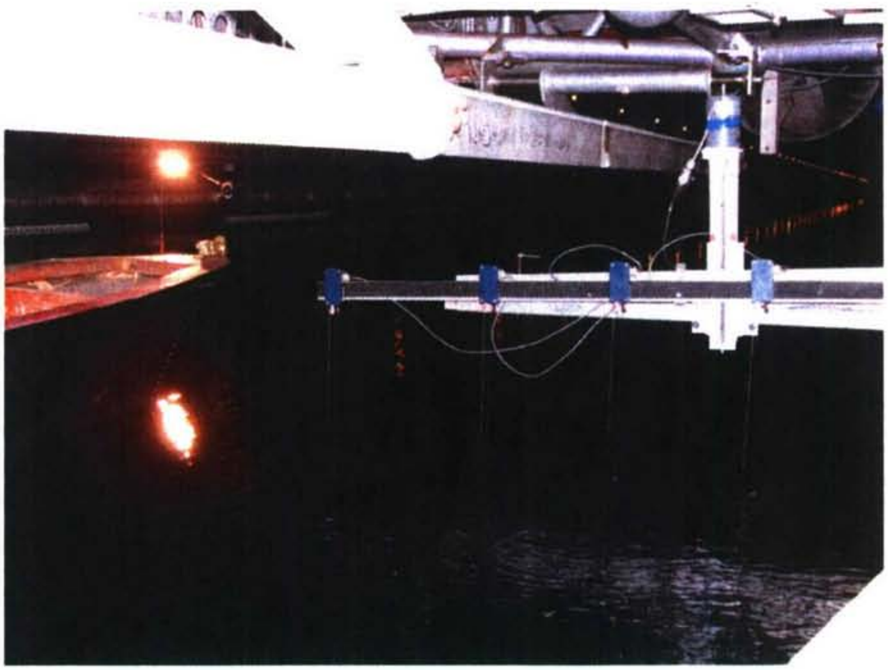


Figure 11 - The Wave Boom with Capacitance Wave Probes Attached

A photosensor is set to trigger data collection when the forward perpendicular of the model is a predefined distance (7.6 m (25.0 ft) in this case) from the capacitance probes. A 133-MHz Pentium-class personal computer, using an ADC488 16-bit analog-to-digital (A/D) converter, collects and stores the data.

The chief limitations of the capacitance probes are that the maximum wave height can exceed the sensing element range, and that a clearly defined water surface is required (i.e., spray or foam will not produce an accurate reading). They have been extensively validated and successfully utilized in numerous experiments over the years.

Calibration

In-situ calibrations are performed after the completion of the test setup. To calibrate the probes, the motorized unislide is traversed in 2.54-cm (1-in) increments for a total range of +/- 7.62 cm (3 in). Data are collected at each increment step for each of the probes. A straight line fit is performed and a slope is calculated and stored for each probe. An in-situ calibration allows for the calibration of the probes, the signal conditioning amplifiers, and the A/D together as a system.

Operating Procedures

Probe zeroes are collected in calm water before each run. The model is then run through the test section, past the probes, at a constant speed. As the model approaches the test section, a strip of reflective tape positioned on the carriage triggers a photosensor placed at the side of the basin which starts data collection. The position of the photosensor and the duration of data collection were adjusted to ensure that the maximum amount of data was collected before tank wall reflections occurred. Data were filtered at 10 Hz with a 3 pole Bessel filter and collected at a sampling rate of 100 Hz for 20 to 30 seconds, depending on model speed.

Presentation and Discussion of Longtudinal Wave Cut Data

Longitudinal wavecuts were obtained at ten model scale speeds, corresponding to their respective full scale speeds detailed in Table 8. The time histories of the wave cut records are presented in Appendix A. The longitudinal wave cut records were analyzed using wave cut analysis software coded at NSWC and based on the longitudinal wave cut theory of Eggers, Sharma and Ward. (8) This analysis yields wave resistance coefficients, across the speed range. These wave resistance coefficients are also presented in Table 8. A plot of the wave resistance versus Froude number is shown in Figure 12. The wave resistance for this hull form reaches a peak near Fn=0.5. This is consistent with fundamental wave resistance calculations by Wigley, which showed a final maxima in the Cw curve (for the Wigley hull form) at Fn=0.476.

Table 8 - Longitudinal Wave Cut Data Obtained on Model 5365

Froude Number	Full-Scale Speed (m/s (ft/s, knots))	Model-Scale Speed (m/s (ft/s, knots))	Run No.	Average Cw (with Truncation correction)
0.14	3.1 (10.1, 6.0)	1.08 (3.53, 2.09)	11, 19	0.034
0.21	4.6 (15.2, 9.0)	1.62 (5.40, 3.14)	12, 20	0.254
0.25	5.4 (17.7, 10.5)	1.88 (6.17, 3.66)	13, 21	0.428
0.29	6.2 (20.3, 12.0)	2.15 (7.06, 4.18)	14, 22	0.598
0.36	7.7 (25.3, 15)	2.69 (8.83, 5.23)	15, 23	1.14
0.43	9.3 (30.4, 18)	3.22 (10.58,6.27)	10, 24	2.288
0.53	11.3 (37.1, 22)	3.94 (12.95, 7.67	9, 25	2.365
0.62	13.3 (43.5, 25.8)	4.62 (15.16, 8.99)	16, 26	1.834
0.72	15.4 (50.6, 30.0)	5.37 (17.63, 10.45)	18, 27	1.954
0.83	18.0 (59.1, 35)	6.27 (20.57, 12.19)	8, 28	0.947

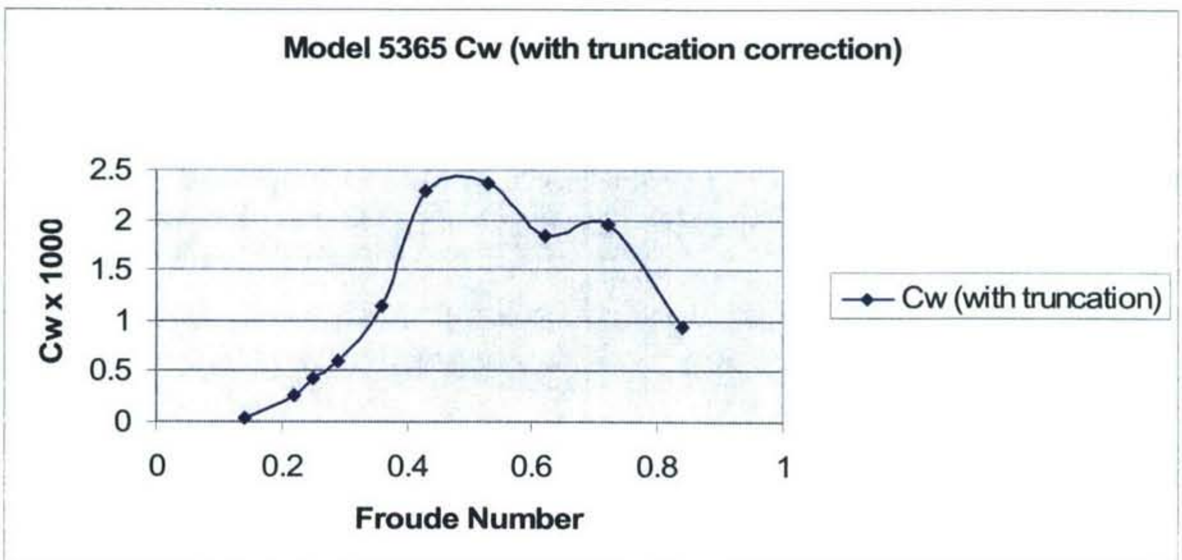


Figure 12 - Model 5365 Wave Resistance Coefficient (C_w) Versus Froude Number

Bow Wave Photographs

A series of bow wave still photographs were obtained on the model during the free-to-sink-and-trim condition. A Nikon F5 still camera with a DCS 620 Digital back was attached to the underside of the carriage and remotely triggered from a laptop computer on the carriage. The resulting photographs, obtained over a speed range corresponding to full scale speeds from 0 knots to 35 knots are documented in Appendix B. The waterlines marked on the model are 1 inch (2.54 cm) apart. Figure 13 shows an example of one of the still photographs.

Figure 13 - Bow wave at 7.67 knots (12.95 fps) model scale corresponding to 22 knots (37.13 fps) full scale; Vertical Displacement at FP= 1.56 in (3.96 cm); Vertical Displacement at AP= -2.48 in (-6.30 cm)

Conclusions

This current set of data obtained on Model 5365 both added to the historical set of data which had been gathered on this model since 1979, and served to resolve some discrepancies in the previous set of resistance data, obtained in 2004. The in-situ calibration performed with this recent set of data, showed that, although there was some drag force felt at the grasshopper bracket, it was less than 4 % of the total drag force. This would not have accounted for the large discrepancy in drag observed in the 2004 data. It is more likely that there was some type of binding in either the grasshopper or at the tow post which resulted in the abnormally low drag measured in 2004. The in-situ calibration procedures that will be adopted for future carriage tests will insure that this problem does not reoccur.

The other data obtained as part of this experiment, including sinkange and trim and longitudinal wave cuts, complemented the existing historic data, providing a comprehensive set of data well-suited to comparison to numerical code predictions. The Froude number range over which this data was obtained results in a data set which represents a naval combatant-type hull form operating at both displacement and planing speeds.

Finally, the still photographs taken at the bow of the model detail the evolution of the bow wave and the contact line along the hull over a well-resolved speed range. The three-dimensional nature of the bow wave and its subsequential breaking is well-documented in these photos.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix A

Wave Cut Time Histories

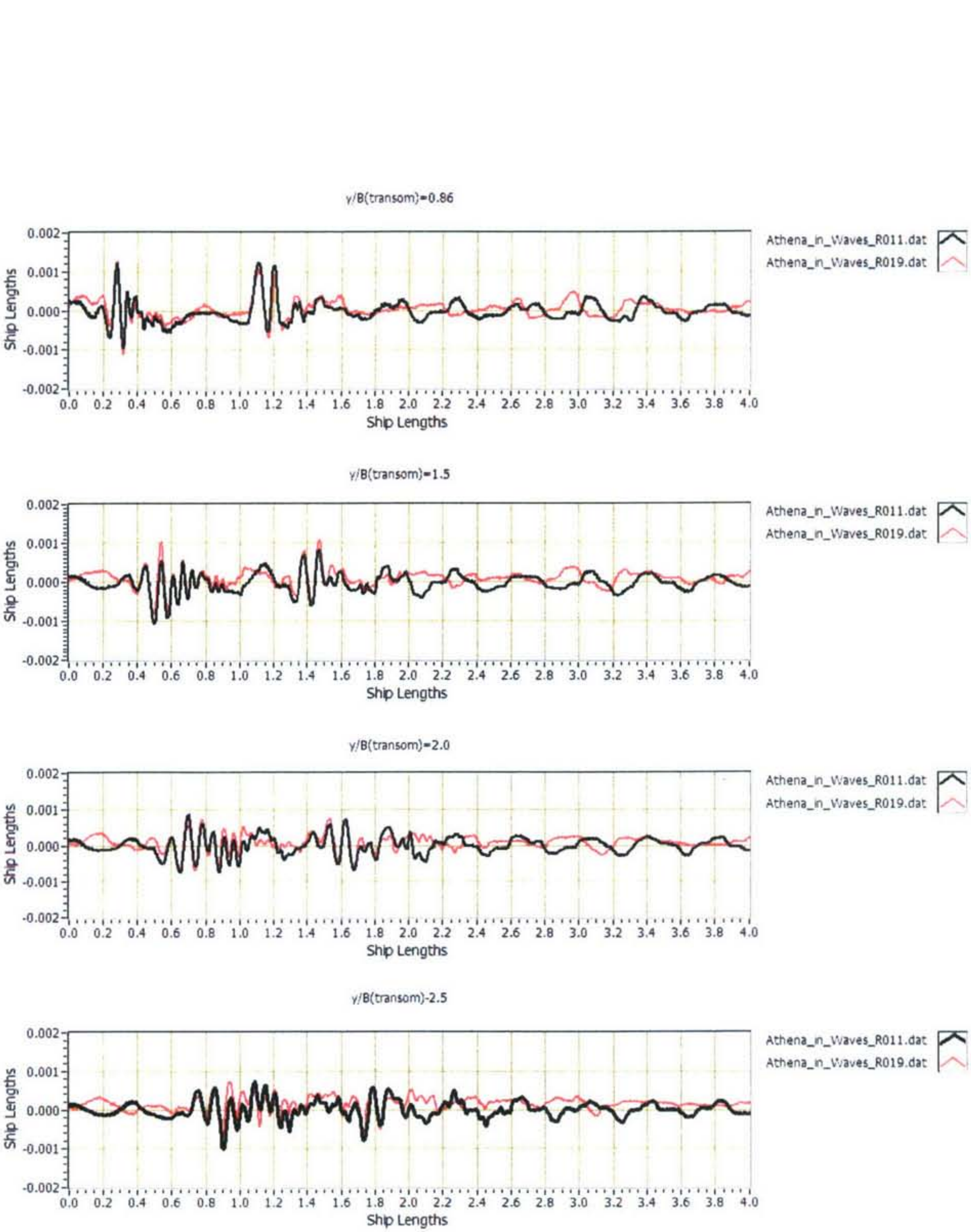


Figure A-1
Longitudinal wavecuts obtained at 2.09 knots (3.53 fps) model scale corresponding to 6 knots (10.1 fps) full scale

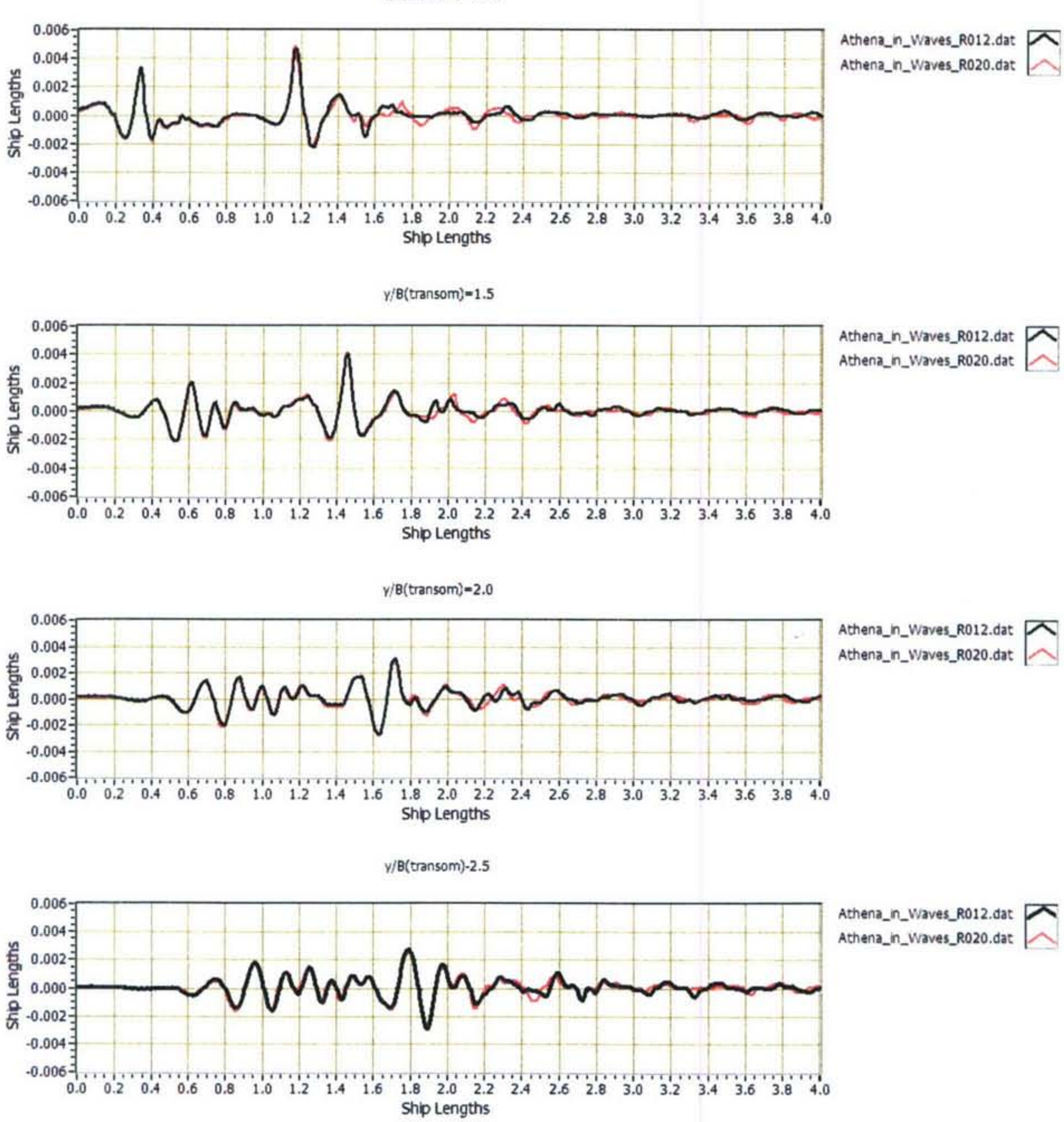


Figure A-2
Longitudinal wavecuts obtained at 3.14 knots (5.3 fps) model scale corresponding to 9 knots (15.2 fps) full scale

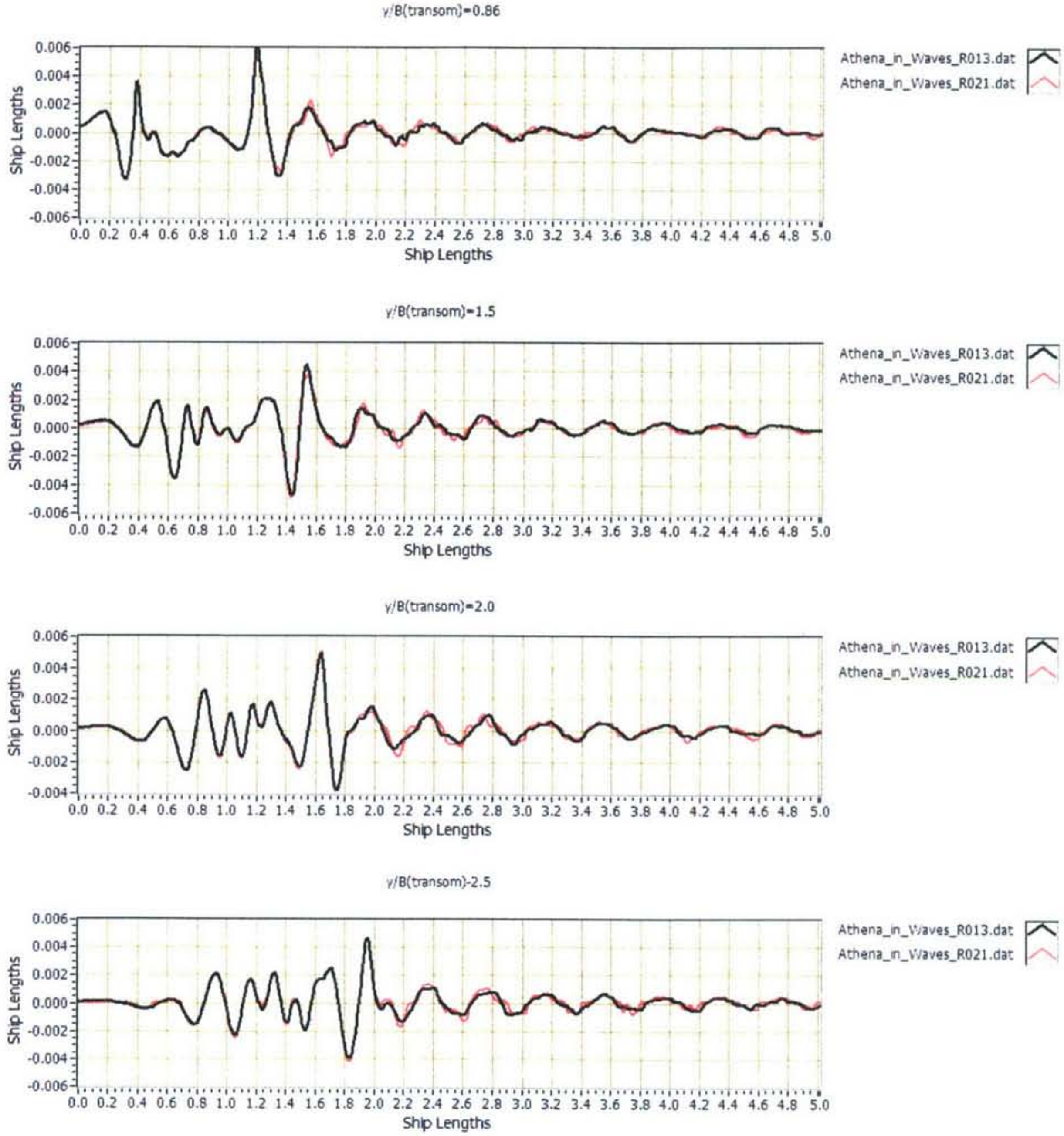


Figure A-3
Longitudinal wavecuts obtained at 3.66 knots (6.17 fps) model scale corresponding to 10.5 knots (17.7 fps) full scale

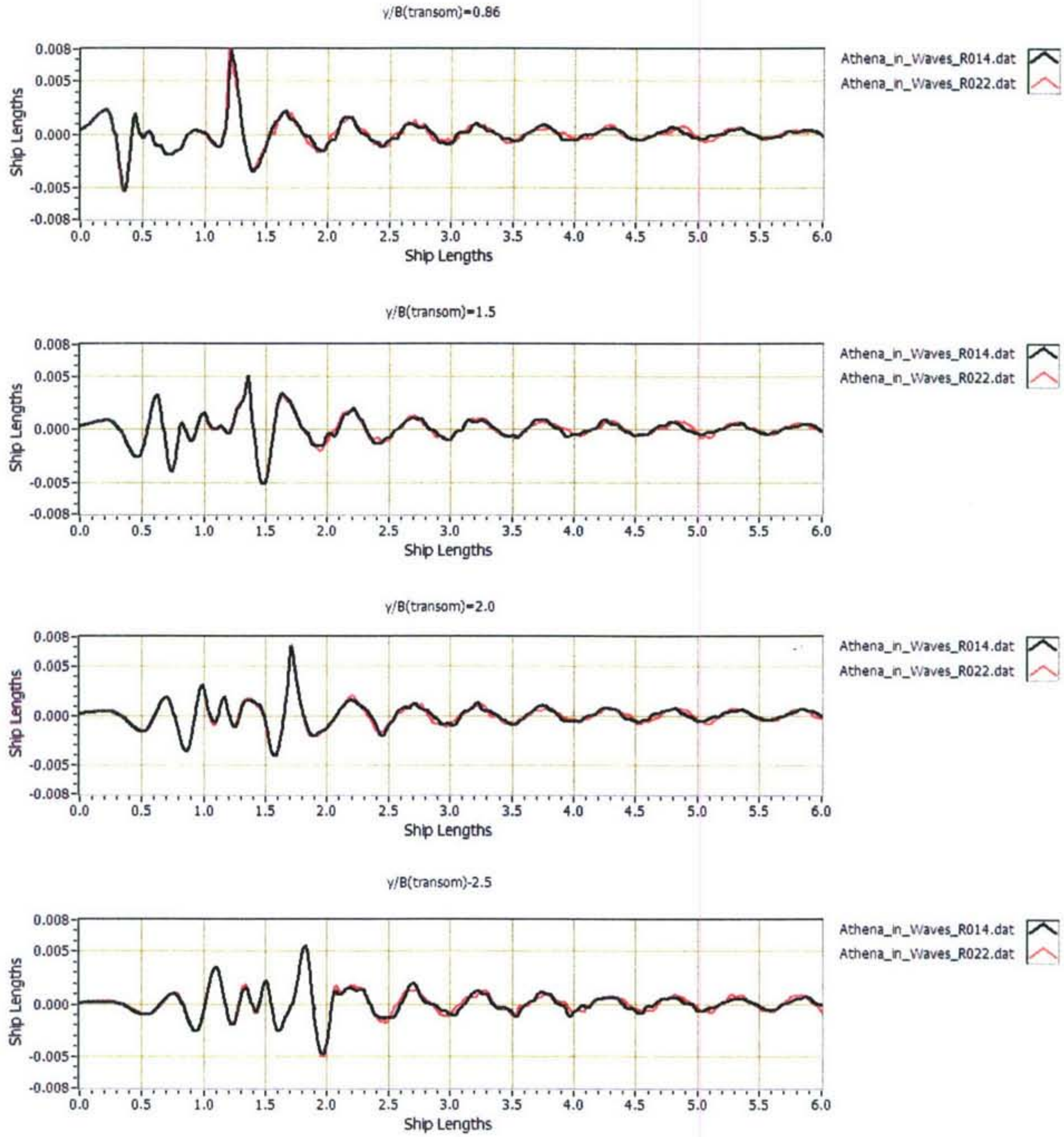


Figure A-4
Longitudinal wavecuts obtained at 4.18 knots (7.06 fps) model scale corresponding to 12 knots (20.3 fps) full scale

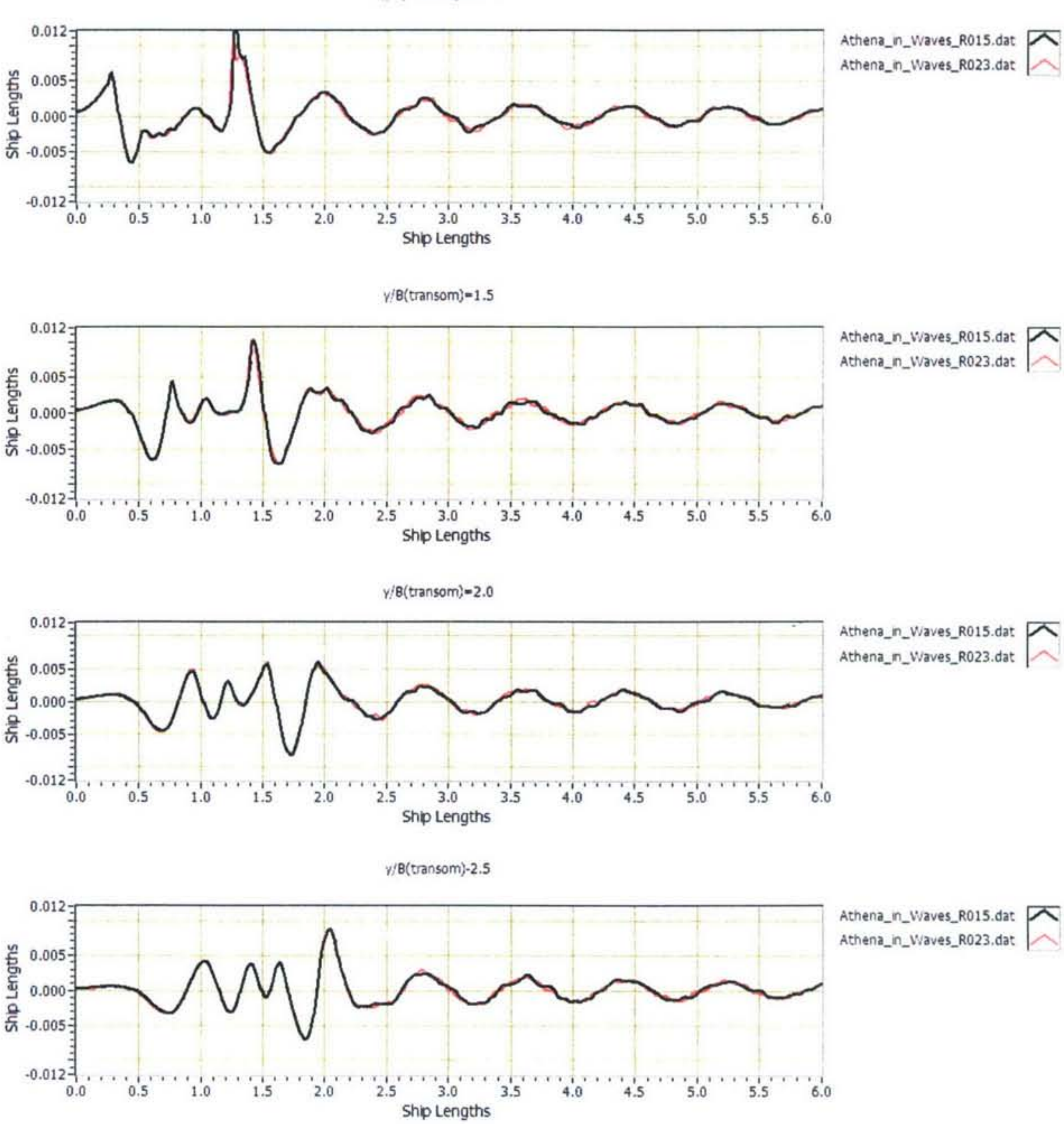


Figure A-5
Longitudinal wavecuts obtained at 5.23 knots (8.83 fps) model scale corresponding to 15 knots (25.3 fps) full scale

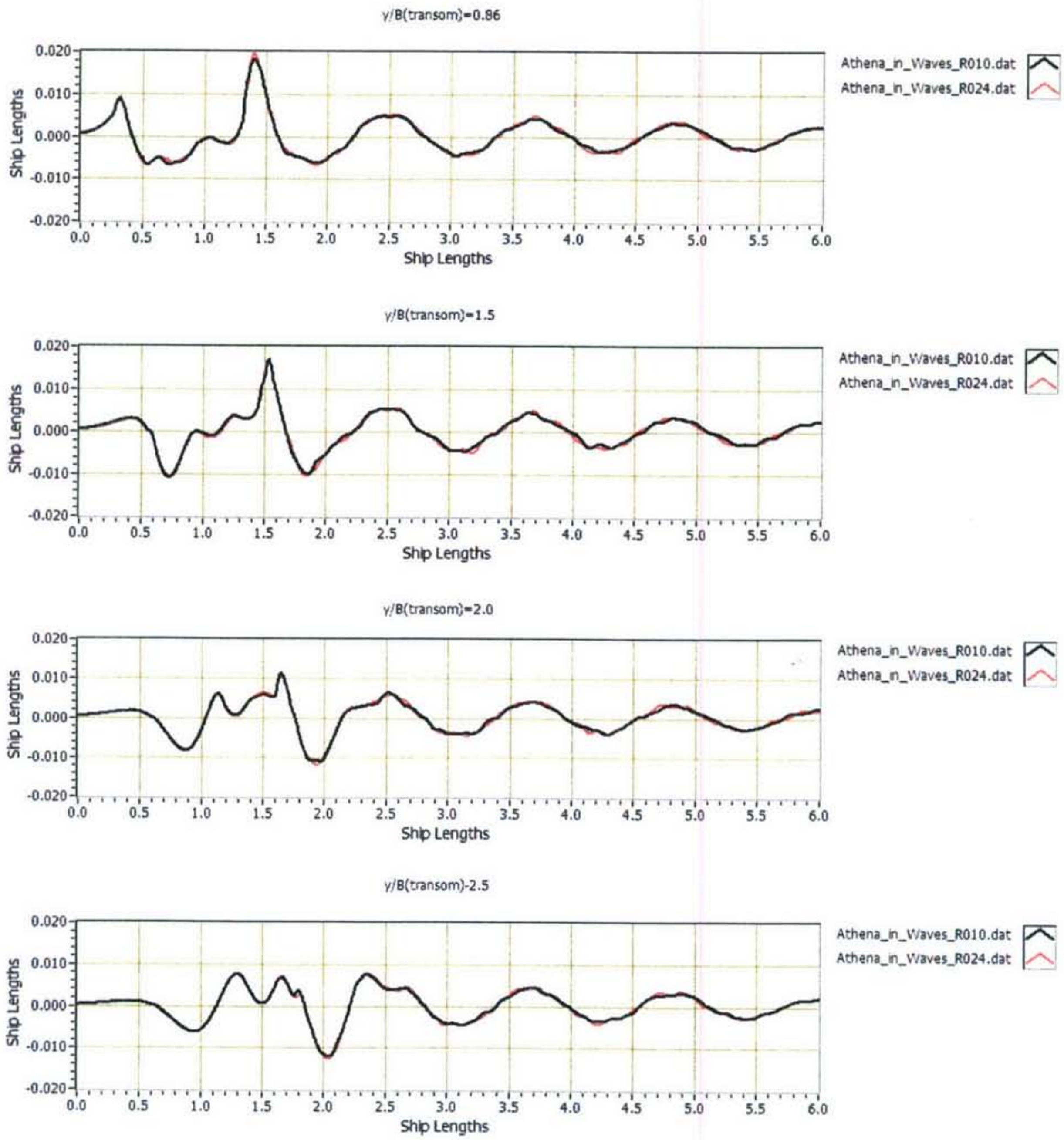


Figure A-6
Longitudinal wavecuts obtained at 6.27 knots (10.58 fps) model scale corresponding to 18 knots (30.4 fps) full scale

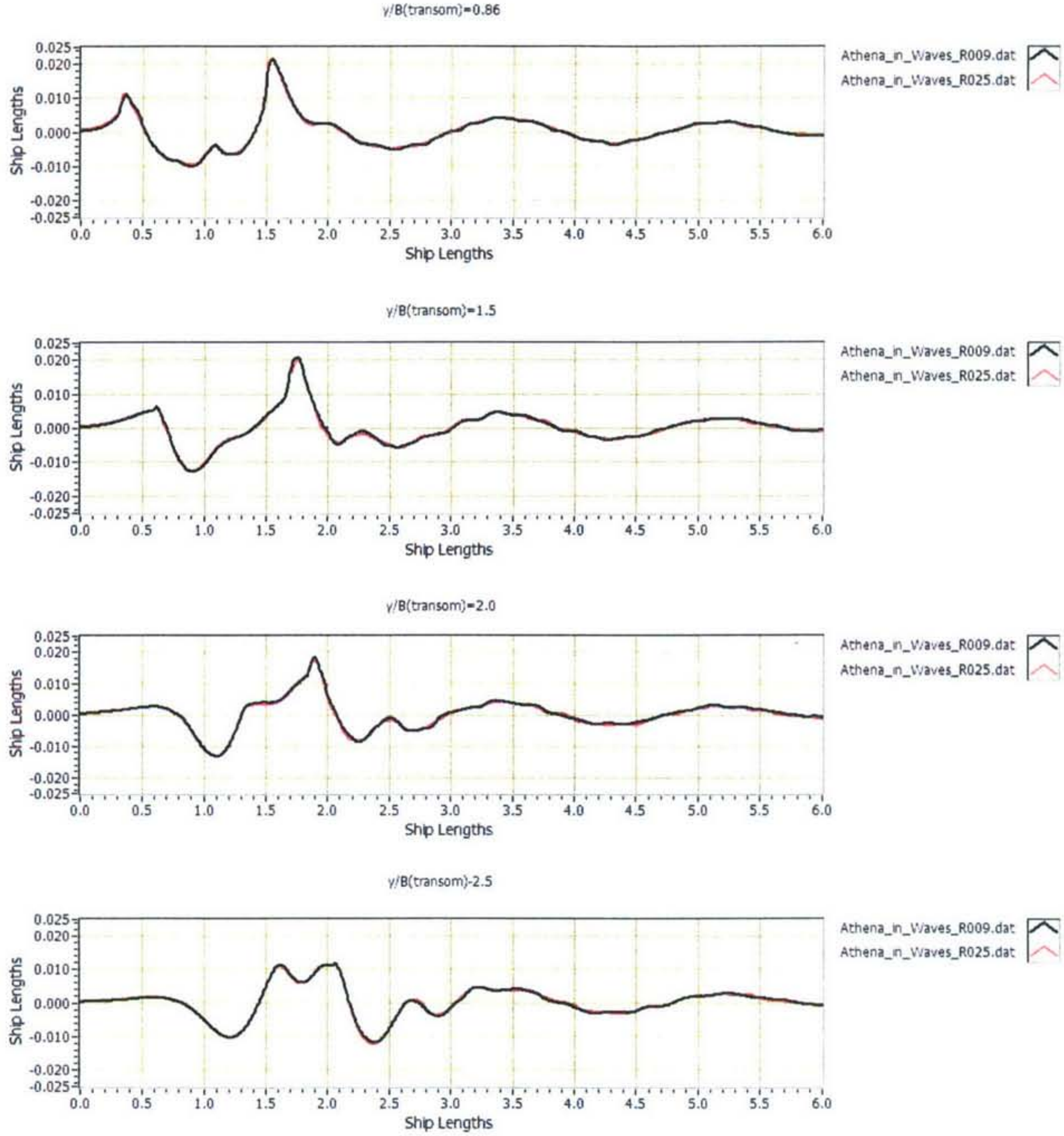


Figure A-7
Longitudinal wavecuts obtained at 7.67 knots (12.95 fps) model scale corresponding to 22 knots (37.13 fps) full scale

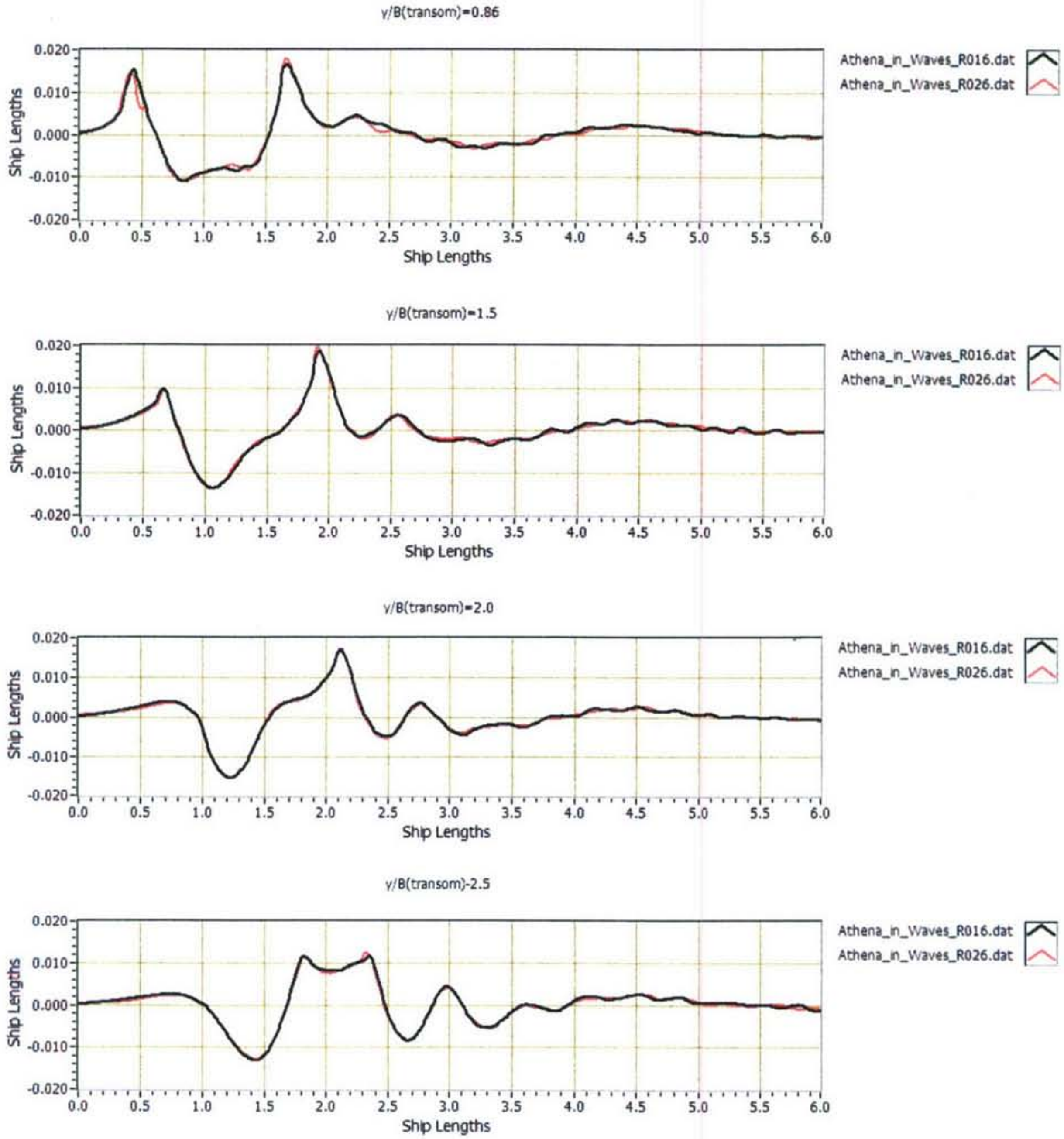


Figure A-8
Longitudinal wavecuts obtained at 8.99 knots (15.16 fps) model scale corresponding to 25.8 knots (43.5 fps) full scale

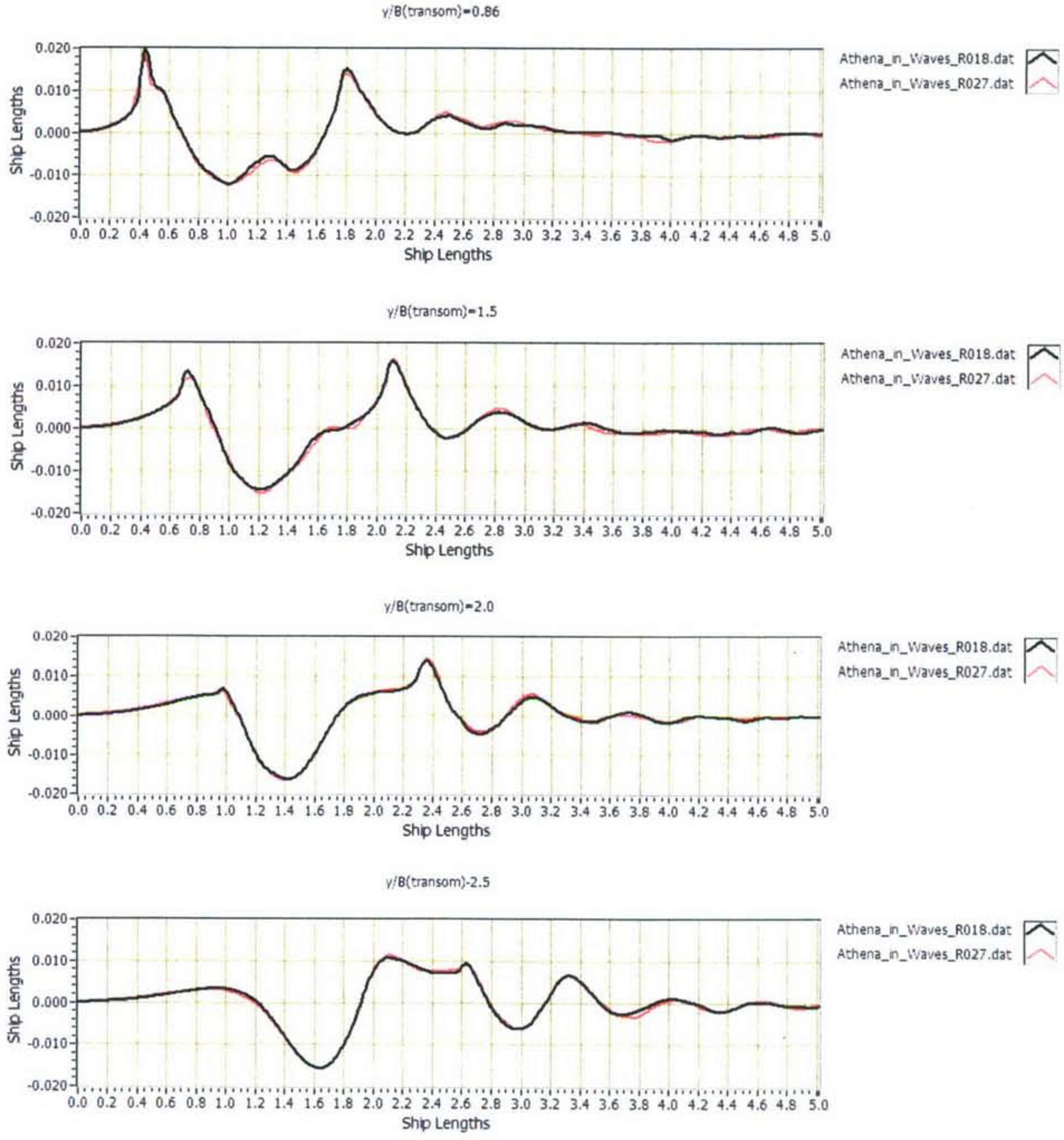


Figure A-9
Longitudinal wavecuts obtained at 10.45 knots (17.63 fps) model scale corresponding to 30 knots (50.6 fps) full scale

Appendix B

**Bow Photo Sequence of
Model 5365 towed in Calm Water**

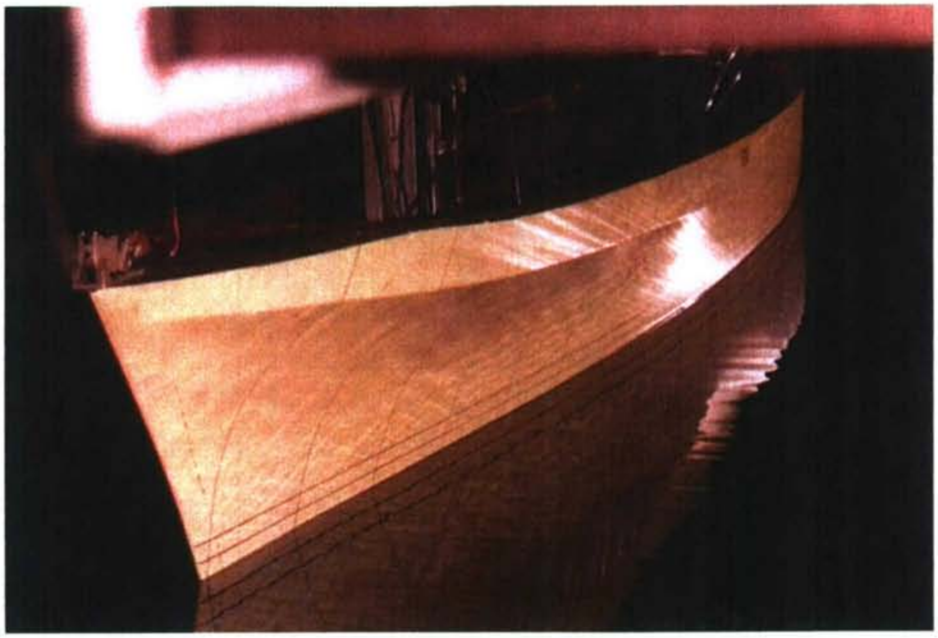


Figure B-1 - Bow wave at 0 speed;
Vertical Displacement at FP=0 inches; Vertical Displacement at AP=0 inches

Figure B-2 - Bow wave at 2.09 knots (3.53 fps) model scale corresponding to 6 knots (10.1 fps) full scale;
Vertical Displacement at FP= -0.059 in (-0.15 cm); Vertical Displacement at AP= -0.036 in (-0.09 cm)

Figure B-3 - Bow wave at 3.14 knots (5.3 fps) model scale corresponding to 9 knots (15.2 fps) full scale; Vertical Displacement at FP= -0.158 in (-0.401 cm); Vertical Displacement at AP= -0.154 in (-0.391 cm)

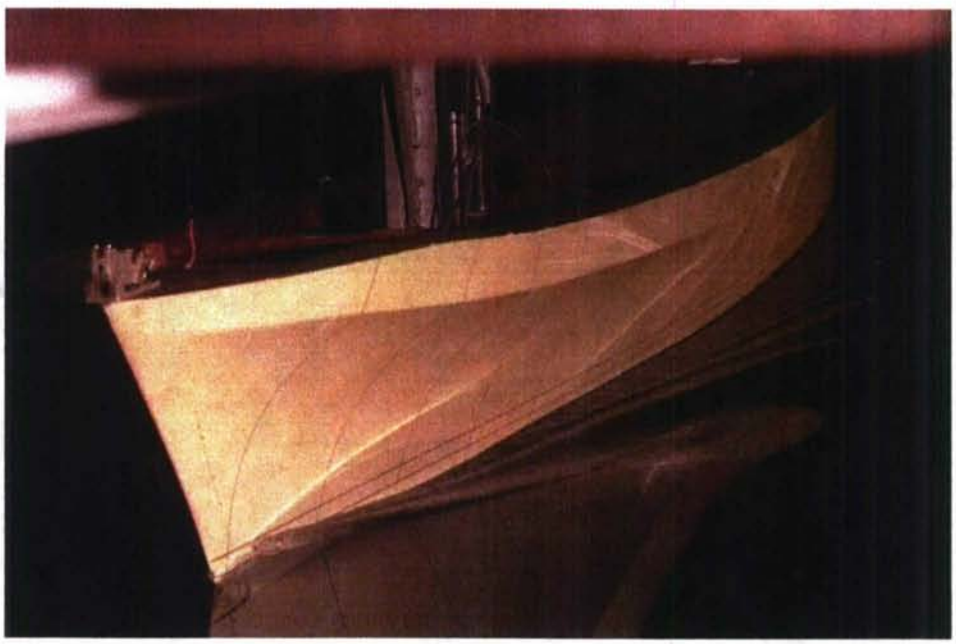


Figure B-4 - Bow wave at 3.66 knots (6.17 fps) model scale corresponding to 10.5 knots (17.7 fps) full scale; Vertical Displacement at FP= -0.192 in (-0.488 cm); Vertical Displacement at AP= -0.235 in (-0.597 cm)

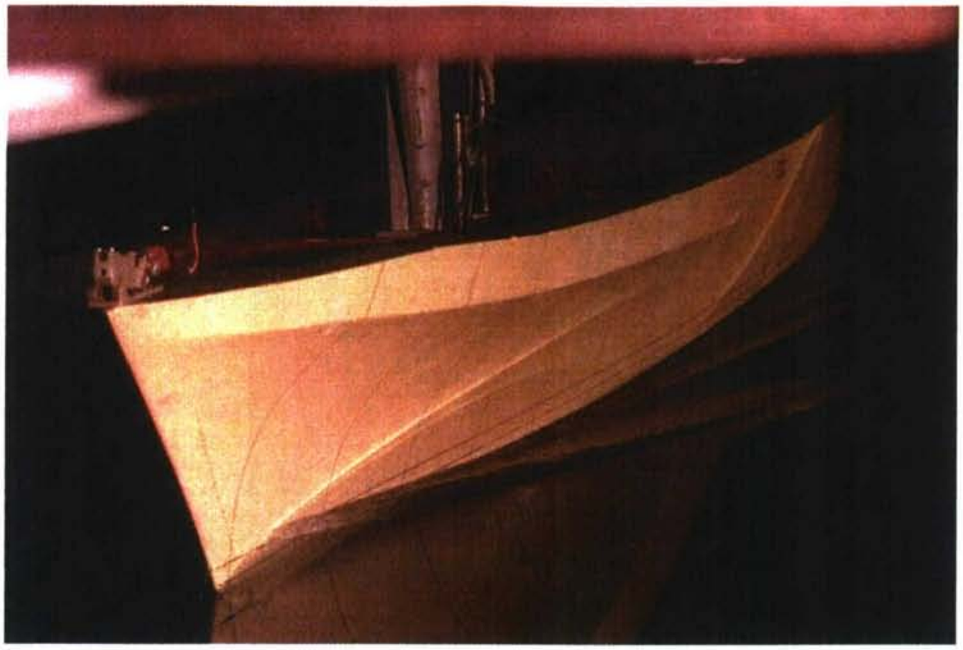


Figure B-5 - Bow wave at 4.18 knots (7.06 fps) model scale corresponding to 12 knots (20.3 fps) full scale; Vertical Displacement at FP= -0.217 in (-0.551 cm); Vertical Displacement at AP= -0.366 in (-0.930 cm)

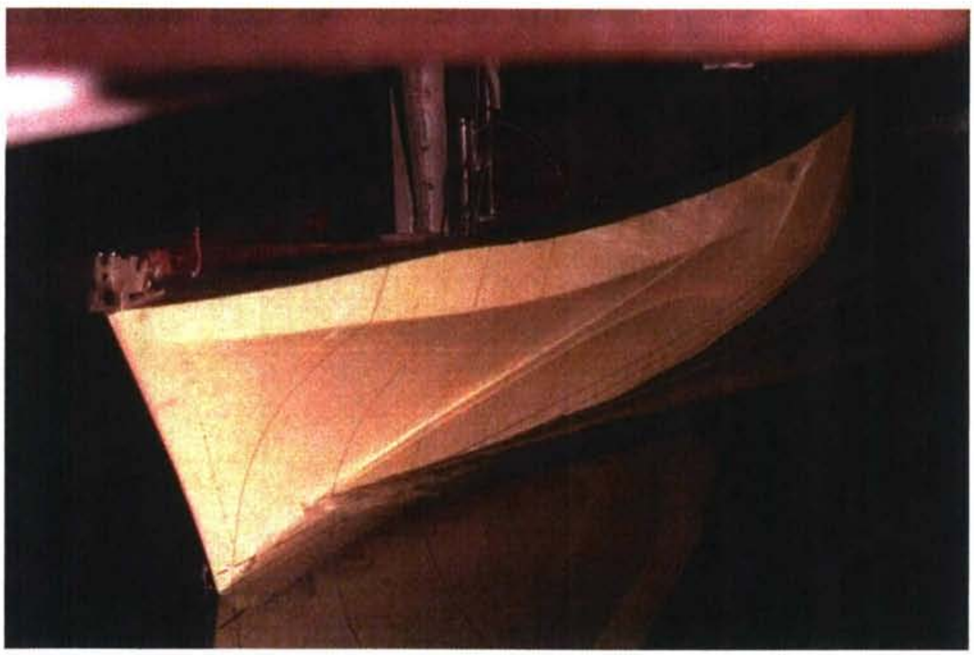


Figure B-6 - Bow wave at 5.23 knots (8.83 fps) model scale corresponding to 15 knots (25.3 fps) full scale; Vertical Displacement at FP= -0.261 in (-0.663 cm); Vertical Displacement at AP= -0.636 in (-1.62 cm)

Figure B-7 - Bow wave at 6.27 knots (10.58 fps)model scale corresponding to 18 knots (30.4 fps) full scale; Vertical Displacement at FP= 0.387 in (2.60 cm); Vertical Displacement at AP= -1.67 in (-4.24 cm)

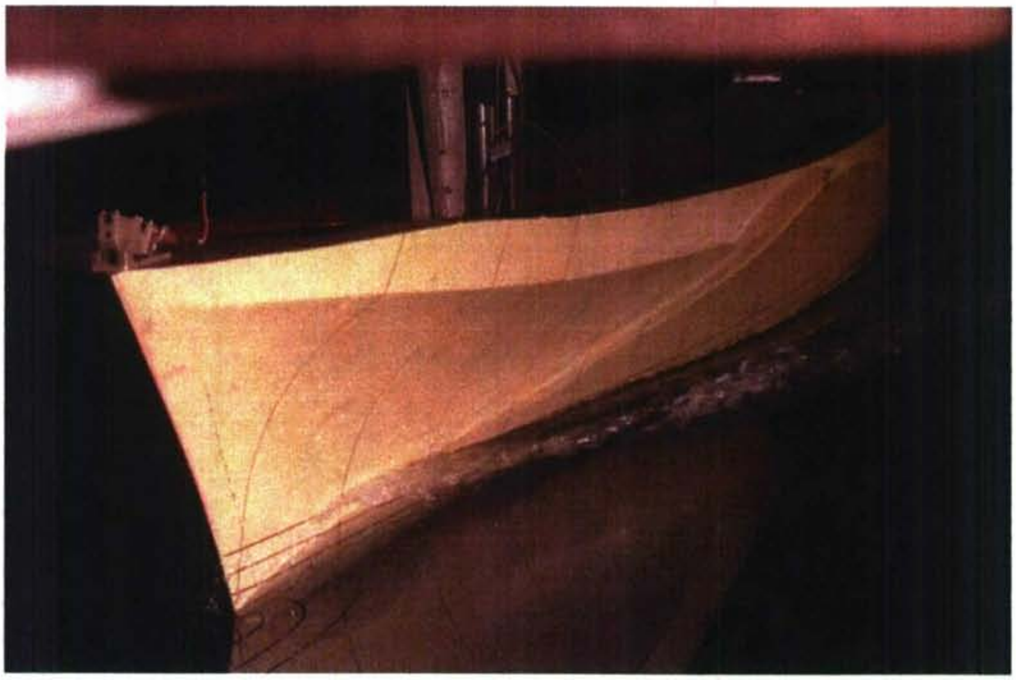


Figure B-8 - Bow wave at 7.67 knots (12.95 fps) model scale corresponding to 22 knots (37.13 fps) full scale; Vertical Displacement at FP= 1.56 in (3.96 cm); Vertical Displacement at AP= -2.48 in (-6.30 cm)

Figure B-9 - Bow wave at 8.99 knots (15.16 fps) model scale corresponding to 25.8 knots (43.5 fps) full scale; Vertical Displacement at FP= 2.07 in (5.26 cm); Vertical Displacement at AP= -2.48 in (-6.30 cm)

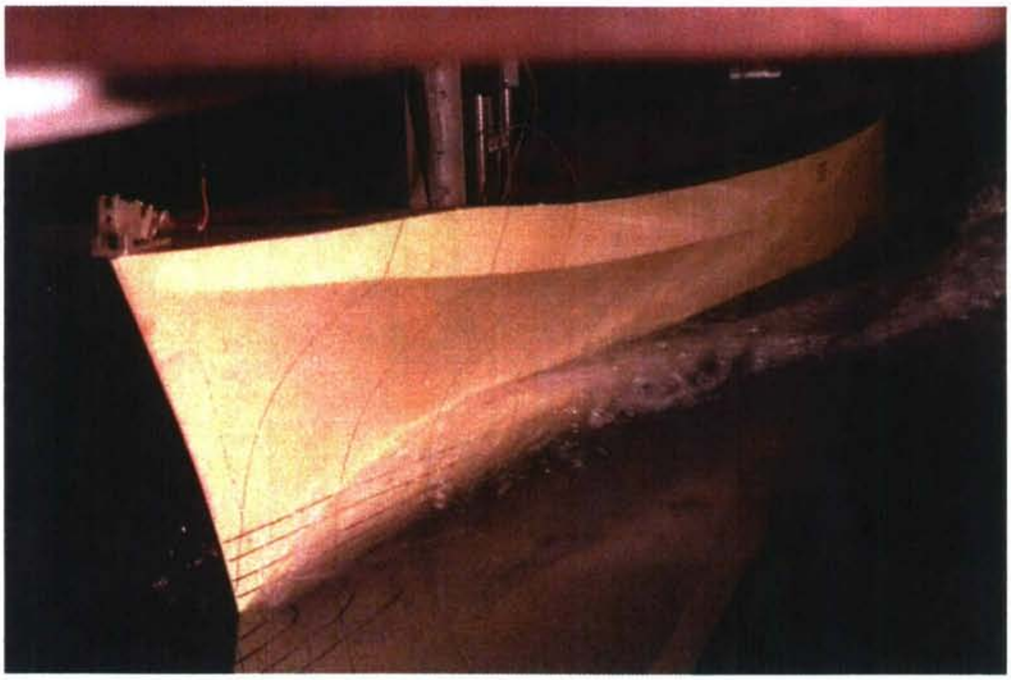


Figure B-10 - Bow wave at 10.45 knots (17.63 fps) model scale corresponding to 30 knots (50.6 fps) full scale; Vertical Displacement at FP= 2.27 in (5.77 cm); Vertical Displacement at AP= -2.27 in (-5.77 cm)

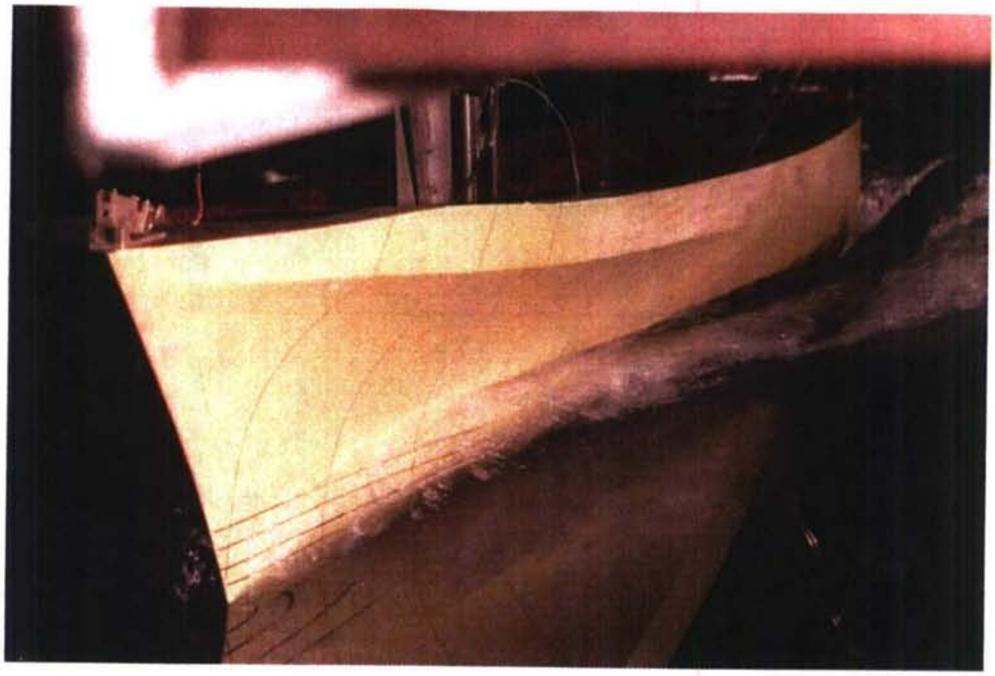


Figure B-11 - Bow wave at 12.19 knots (20.57 fps) model scale corresponding to 35 knots (59.07 fps) full scale; Vertical Displacement at FP= 2.27 in (5.77 cm); Vertical Displacement at AP= -2.09 in (-5.31 cm)

References

1. Wilson, W., Fu, T., " The Measured and Predicted Wave Field of Model 5365: An Evaluation of Current CFD Capability," 26th Symposium on Naval Hydrodynamics, Rome, Italy, 2006

2. Fu, T., Karion, A., Rice, J., Walker, D., "Experimental Study of the Bow Wave of the R/V Athena I," 25th Symposium on Naval Hydrodynamics, St. John's, Newfoundland, Canada, 2004

3. Fu, Thomas et. al, "Characterization of the Steady Wave Field of the High Speed Transom Stern Ship – Model 5365 Hull Form, NSWCCD-50-TR-2005/046, September 2005

4. Fu, Thomas et. al, "Bow Wave Measurements of the R/V Athena I: 2003", NSWCDD-50/TR/2005/034, December 2005

5. Fu, Thomas et. al, "Bow Wave Measurements of the R/V Athena I: 2004", NSWCDD-50/TR/2005/035, December 2005

6. Fu, Thomas et. al, "Characterization of the Bubble Flow and Transom Wave of the R/V Athena I", NSWCCD-TR-50-2007/049, May 2007

7. Jenkins, D. S., "Resistance Characteristics of the High Speed Transom Stern Ship R/V Athena in the Bare Hull Condition, Represented by DTNSRDC Model 5365," DTNSRDC-84/024, June 1984.

8. Eggers, K.W.H., Sharma, S. D. and Ward, L.W., "An Assessement of Some Experimental Methods for Determining the Wavemaking Characteristics of a Ship Form," SNAME Transactions, Volume 75, 1967.

Distribution

Copies

1	DTIC	
IIHR		
1		F. Stern
1		J. Longo
ONR		
1	331	P. Purtell
SAIC		
1		D. Wyatt
1		D. Dommermuth

DIVISION DISTRIBUTION

1	3442	TIC (pdf only)
1	5050	A. Reed
1	5060	D. Walden
1	5200	D. Walker (w/o enclosure)
1	5200	D. Hendrix
1	5400	J. Gorski
1	5400	W. Wilson
1	5400	R. Miller
1	5600	ff(w/o enclosure)
1	5600	T. Fu (w/o enclosure)
1	5600	A. Fullerton (w/o enclosure)
1	5600	L. Russell (w/o enclosure)
1	5600	J. Rice (w/o enclosure)